Propulsion Airframe Aeroacoustics Technology Evaluation and Selection Using a Multi-Attribute Decision Making Process and Non-Deterministic Design

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The Systems Analysis Branch at NASA Langley Research Center has investigated revolutionary Propulsion Airframe Aeroacoustics (PAA) technologies and configurations for a Blended-Wing-Body (BWB) type aircraft as part of its research for NASA's Quiet Aircraft Technology (QAT) Project. Within the context of the long-term NASA goal of reducing the perceived aircraft noise level by a factor of 4 relative to 1997 state of the art, major configuration changes in the propulsion airframe integration system were explored with noise as a primary design consideration. An initial down-select and assessment of candidate PAA technologies for the BWB was performed using a Multi-Attribute Decision Making (MADM) process consisting of organized brainstorming and decision-making tools. The assessments focused on what effect the PAA technologies had on both the overall noise level of the BWB and what effect they had on other major design considerations such as weight, performance and cost. A probabilistic systems analysis of the PAA configurations that presented the best noise reductions with the least negative impact on the system was then performed. Detailed results from the MADM study and the probabilistic systems analysis will be published in the near future, Refs. 1 and 2.

Nomenclature

PAA	=	Propulsion Aiframe Aeroacoustics
BWB	=	Blended Wing Body
QAT	=	Quiet Aircraft Technology
MADM	=	Multi-Attribute Decision Making
TOPSIS	=	Technique for Order Preference by Similarity to Ideal Solution

I. Introduction

THE purpose of this paper is to demonstrate an application of advanced design methods, involving a Multi-Attribute Decision Making (MADM) process and probabilistic conceptual design analysis. The Systems Analysis Branch at NASA Langley Research Center has investigated revolutionary Propulsion Airframe Aeroacoustics (PAA) technologies and configurations for a 300-passenger Blended-Wing-Body (BWB) as part of its research for NASA's Quiet Aircraft Technology (QAT) Project. Using aircraft configuration and advanced technology applied to propulsion airframe integration, PAA seeks to reduce net radiated noise through the aeroacoustic effects created by propulsion airframe integration[2]. In order to meet the stringent long-term NASA goal of reducing perceived aircraft noise levels by a factor of 4 relative to 1997 state of the art, several configuration changes to the propulsion/airframe system were explored with noise as a primary design consideration. The

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exploration considered a broad range of candidate technologies and design concepts. Methodologies were therefore needed to quickly assess and rank the technologies and design concepts and then perform robust systems analysis on the down-selections.

The procedure employed was inspired by the Technology Ranking Methodology used at the Aerospace Systems Design Laboratory (ASDL) at the Georgia Institute of Technology[3]. An initial down-select and assessment of candidate PAA technologies for the BWB was performed using a MADM process consisting of organized brainstorming and use of decision-making tools. A Morphological Matrix was used to functionally decompose the entire aircraft system into subsystems and to brainstorm the technologies applicable to each subsystem. A qualitative technology assessment was performed using a Pugh Evaluation Matrix, which focused on what effect the PAA technologies had on both the overall noise level of the BWB and what effect they had on other major design considerations such as weight, performance, and cost. A ranking of the technologies relative to the BWB baseline and a quantification of the qualitative assessments were then obtained using the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). Candidate configurations for further study were then formed by combining highly ranked compatible technologies. A systems analysis based on non-deterministic, probabilistic design methods was then performed on a selected few configurations to assess their weight and performance in more detail.

II. Morphological Matrix and Pugh Evaluation Matrices

The MADM process began with the construction of a Morphological Matrix containing a list of possible PAA technologies and design concepts that could be applied to the BWB baseline vehicle. The technologies and design concepts were selected through literature searches and Integrated Product Team (IPT) brainstorming. The list, as shown in Fig. 1, consisted of a variety of inlet and nozzle types, engine concepts, trailing-edge geometries, engine placement arrangements, and high-lift technologies.

Propulsion System type	Single	Hybrid		
Inlet type	Circular	Semi-Circular BLI	Mail Slot BLI S-duct	…
Engine Size	Large Main	Medium Distributed	Small Distributed	…
Engine Type	Gas Turbine	Gas Turbine powered Ducted Fans	Electric (Fuel Cell) Driven Ducted Fans	
Engine Mount	Podded	Buried in Airframe		
Engine Placement	Rear Mounted	Mid Mounted	Forward Mounted	…
Fuel Type	Hydrocarbons	Liquid Hydrogen		
Trailing Edge Geometry	Current BWB	Fixed Trailing Edge/Tail Ext.	Retractable Trailing Edge/Tail Ext.	…
Trailing Edge Noise Control	none	TE Active Flow Control (Sucking or Blowing)	Serrated TE	
Nozzle	Circular Nozzle	Distributed Exhaust Nozzle	High Aspect Ratio Nozzle (HARN)	…
High Lift	Flaps, Slats	Flaps and Slats with Continuous Moldline Tech.	No Flaps and Slats, Thrust Vectoring	…
* Baseline				

Figure 1. Subset of the Morphological Matrix.

Weights, Performance and Cost Requirements (Evaluation Criteria)	Customer Importance	Inlet Types				
		Semi-circular BLI	Freestream S-duct	Mail Slot BLI S-duct	Leading Edge Mail Slot Inlet	Datum
Empty Weight	10	9	9	9	9	10
Fuel Weight	10	11	7	11	10	10
Low Speed Lift	0	9	7	7	9	10
Low Speed Drag	0	11	7	11	13	10
Cruise Drag	0	13	7	13	13	10
Low Speed Thrust	0	11	9	11	9	10
Range	0	11	7	11	10	10
Initial Cruise Altitude Capibility	4	11	9	11	10	10
TOFL	5	11	9	11	10	10
LdgFL	4	10	9	9	10	10
CO2	4	11	7	11	10	10
NOx	4	11	7	11	10	10
Stability/Balance	5	10	10	10	10	10
Reliability / maintainability	5	10	10	10	10	10
Safety	8	10	10	10	10	10
Passenger Compartment	4	9	9	9	9	10
Fuel Capacity	2	9	9	9	7	10
Cabin Noise	2	10	10	10	10	10
RDT&E Cost	7	9	10	9	9	10
Production Cost	7	10	10	10	9	10
DOC + I	0	11	9	11	10	10

Figure 2. Pugh Evaluation Matrix.

The PAA technologies in the Morphological Matrix were qualitatively assessed using a Pugh Evaluation Matrix[4], shown in Fig. 2, which helped estimate the effects of each technology on the overall system and their impact on design requirements. The design requirements included performance metrics (empty weight, fuel weight, etc.), cost metrics (RDT&E, DOC, etc.), reliability, safety, and noise. Expert opinion from selected individuals in various industry, academia and government organizations was solicited to ensure thorough understanding of the technology impacts and subsystem interaction. First, they were asked to estimate the relative customer importance of each design requirement in the Pugh Evaluation Matrix by choosing a weight between 1 and 10, with 10 representing the most significant criterion. When expert opinions differed, an average value or a value judged as the most appropriate was chosen based on the reasoning behind the various opinions. Subsequently, they were asked to judge if a technology had positive, negative, or no impact on each evaluation criteria relative to the BWB baseline vehicle, and to determine if the effect was strong, medium, normal, or weak in magnitude. The qualitative judgments were mapped to numeric values (1, 4, 7, 9, 10, 11, 13, 16, and 19), with 10 representing the baseline value.

III. Noise Scale Factor

Although noise was the primary concern for this study, other system requirements needed to be considered to result in a feasible design. However, relative importance of design requirements was difficult to identify between noise and performance related criteria (i.e., Fan noise vs. Empty Weight); therefore, two independent Pugh Evaluation matrices were constructed, one for noise and one for performance, weights and cost requirements. Once they were completed independently, a Noise Scale Factor (NSF) was created to help combine the two independent matrices into one. The NSF was defined as a multiplier for the noise related weights and [1-NSF] was the performance/weight/cost multiplier. The noise scale factor ranged between 0 and 1, where 0 indicated that noise considerations played no role in the final technology ranking and 1 indicated that the ultimate ranking only depended on noise criteria.

(1-NSF)*Customer Importance

Weights, Performance and Cost Requirements (Evaluation Criteria)	Customer Importance	Inlet Types: Semi-circular BLI	Freestream S-duct	Mail Slot BLI S-duct	Leading Edge Mail Slot Inlet	Datum
Empty Weight	10	9	9	9	9	10
Fuel Weight	10	11	7	11	10	10
Low Speed Lift	0	9	7	7	9	10
Low Speed Drag	0	11	7	11	13	10
Cruise Drag	0	13	7	13	13	10
Low Speed Thrust	0	11	9	11	9	10
Range	0	11	7	11	10	10
Initial Cruise Altitude Capibility	4	11	9	11	10	10
TOFL	5	11	9	11	10	10
LdgFL	4	10	9	9	10	10
CO2	4	11	7	11	10	10
NOx	4	11	7	11	10	10
Stability/Balance	5	10	10	10	10	10
Reliability / maintainability	5	10	10	10	10	10
Safety	8	10	10	10	10	10
Passenger Compartment	4	9	9	9	9	10
Fuel Capacity	2	9	9	9	7	10
Cabin Noise	2	10	10	10	10	10
RDT&E Cost	7	9	10	9	9	10
Production Cost	7	10	10	10	9	10
DOC + I	0	11	9	11	10	10

NSF*Customer Importance

Noise Requirements		Customer Importance	Inlet Types: Semi-circular BLI	Freestream S-duct	Mail Slot BLI S-duct	Leading Edge Mail Slot Inlet	Datum
Takeoff Noise	High-Lift Noise	8	10	10	10	10	10
	Trailing Edge Noise	6	10	10	10	10	10
	Aft Fan Noise	10	10	10	10	10	10
	Forward Fan Noise	5	9	11	10	13	10
	Turbine Noise	7	10	10	10	10	10
	Nozzle/Jet Noise	9	10	10	10	10	10
Landing Noise	High-Lift Noise	10	10	10	10	10	10
	Trailing Edge Noise	6	10	10	10	10	10
	Aft Fan Noise	10	10	10	10	10	10
	Forward Fan Noise	4	9	13	10	13	10
	Turbine Noise	7	10	10	10	10	10
	Nozzle/Jet Noise	5	10	10	10	10	10
	Landing Gear	9	10	10	10	10	10

Figure 3. Noise Scale Factor Applied to both Pugh Evaluation Matrices.

For example, if NSF was equal to 0.2, then the performance/weight/cost factor became 0.8, which means that 20 percent of the assessment depended on noise and 80 percent depended on performance, weight and cost. This allowed a sensitivity study of performance-related criteria versus noise criteria and customer flexibility in choosing the importance of reduced noise relative to performance, weight, and cost in the final design decision.

IV. Technique for Order Preference by Similarity to Ideal Solution

TOPSIS[5] is another useful MADM tool, which was used to evaluate quantitatively the qualitative judgments made in the Pugh Evaluation Matrix, and to provide a ranking of the technologies, including the baseline. TOPSIS is based on an algorithm, which ranks the technologies according to their Euclidean distance to an ideal solution. The relative importance of the design requirements was maintained in the form of weights, as mentioned above.

The first TOPSIS step consisted of non-dimensionalizing the center values in the Pugh matrix by dividing each of them by the norm of the total outcome vector (sum of squares of a criterion) of the criterion at hand, as shown in Fig. 4a.

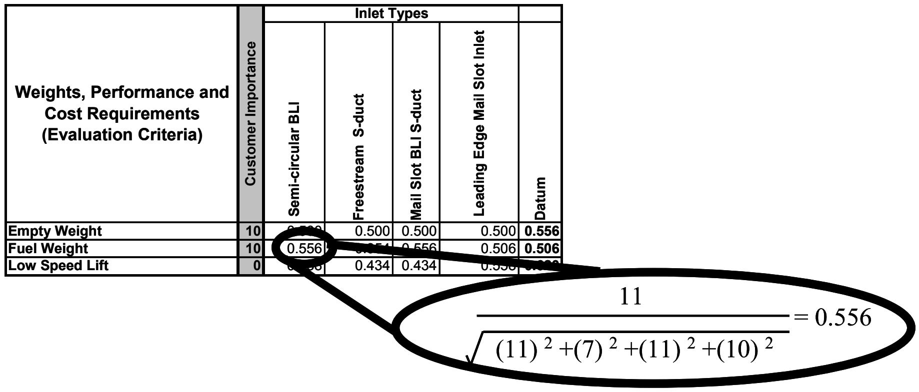

Figure 4a. Subset of the Non-Dimensionalized Pugh Matrix.

The second step was to establish relative importance of the criteria by applying the noise scale factor to the weights and by multiplying the matrix values by the normalized weights for each criterion. Fig4b. shows an example for NSF =0.2.

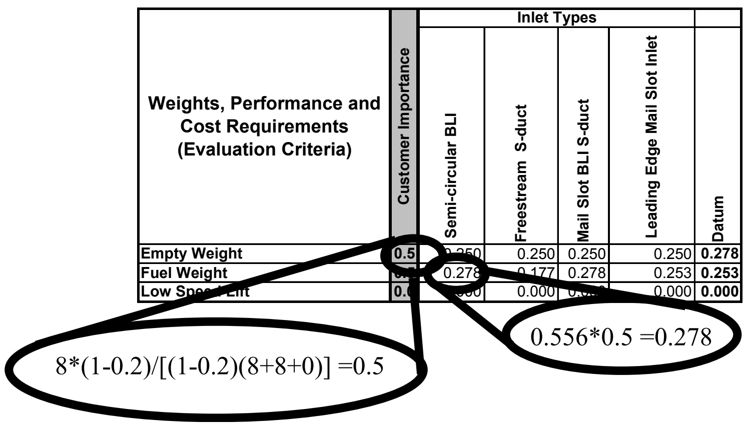

Figure 4b. Subset of the Non-Dimensionalized Matrix Multiplied by Non-Dimensionalized Weights, and by the NSF.

The third step consisted of building positive and negative ideal solutions to compare against. The positive ideal solution corresponded to the set of best or maximum values of each row. Conversely, the negative ideal solution constituted the set of worst or minimum values of each row of the Pugh Matrix. From the small matrix shown in Fig. 4b, the respective positive and negative ideal solutions are: A^+ = {0.250, 0.278, 0} and A^- = {0.250, 0.177, 0}, where A^+ and A^- are the vectors containing the ideal solutions and the three elements correspond to the three rows in the matrix.

Once the ideal solutions were known, the separation of each matrix value from the ideals was measured by the n-dimensional Euclidean distance, defined in Eq. (1).

$$S^{+/-} = \sqrt{\sum (\text{Matrix Value} - \text{Pos/Neg Ideal Value})^2} \quad (1)$$

In the example shown in Fig. 4b, the Euclidean distances for Semi-circular Boundary Layer Ingestion (BLI) inlets are: S+ = (0.250-0.250)*2+(0.278-0.278)*2 + (0-0)*2 = 0 and S- = (0.250-0.250)*2+(0.278-0.177)*2 + (0-0)*2 = 0.101. These Euclidean distances were then translated into a single metric, called the Relative Closeness to the Ideal Solution, which is computed as shown in Eq. (2)

$$C_i = S_{i^-} / (S_{i^+} + S_{i^-}) \quad (2)$$

In the example above, Semi-circular BLI has a Relative Closeness C_{BLI} = 0.101/(0 + 0.101) = 1. The technologies were then ranked based on their closeness to the ideal solution, where best was equal to 1 and worst equal to 0.

Figures 5a and 5b below show the results obtained with all the technologies and all the design requirements considered. Figure 5a shows the inlet technology ranking for NSF = 0.5. The mail slot was found to be the best inlet choice, if noise and weight/performance/cost were chosen to have equal importance. Figure 5b shows the inlet results for all NSF values. It is observed that when performance is highly weighted (low NSF), the BLI and mail slot inlets are the best choices. However, if the importance of noise reduction is increased (high NSF), the technology ranking shifts and the leading edge mail slot, and s-duct inlets become better choices. The latter two, have longer ducts and have more surface area for acoustic liner treatment and shielding, which is why they present better options for lower noise technologies. The inlet flow losses due to the duct lengths explains their lower ranking on the performance side.

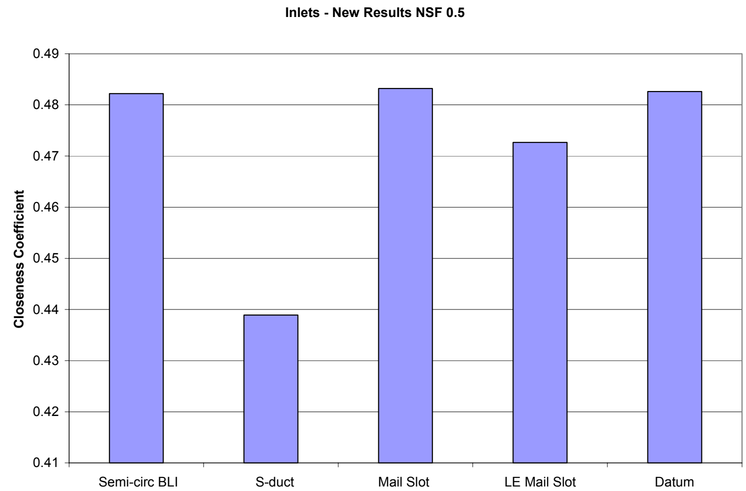

Figure 5a. TOPSIS Results for NSF= 0.5.

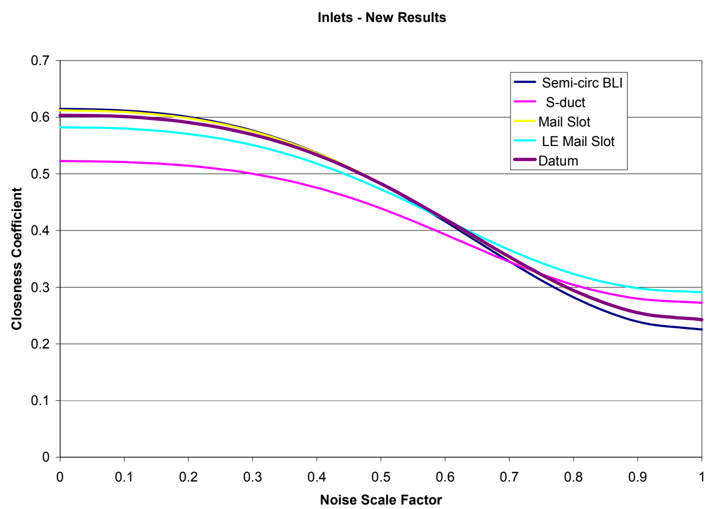

Figure 5b. TOPSIS Results as a function of all NSFs.

The TOPSIS assessment was performed on all the technologies and design concepts. The initial weights and matrix values were based on qualitative assessments; therefore, a check for robustness was needed to give the assessments more credibility. Robustness was assessed by performing a sensitivity analysis on the TOPSIS study. The Pugh matrix center values were varied according to six different mapping scenarios, and the design requirement customer importance weights were varied according to ten weighting scenarios. A scenario was defined as a specific perturbation pattern of the original matrix content. For example, in one mapping scenario (MS5), all the 4's were changed to 5's and all the 16's were changed to 15's in the following series (1, 4, 7, 9, 10, 11, 13, 16, and 19). Figures 6a and 6b present the mapping and weighting scenarios used. The highlighted numbers represent the numbers that were changed relative to the first scenario.

Mapping Scenario					
MS1	MS2	MS3	MS4	MS5	MS6
19	19	19	19	19	19
16	15	17	16	15	17
13	12	14	14	13	15
11	11	11	12	11	13
10	10	10	10	10	10
9	9	9	8	9	7
7	8	6	6	7	5
4	5	3	4	5	3
1	1	1	1	1	1

Figure 6a. Mapping Scenarios.

		Weighting Scenario									
		WS1	WS2	WS3	WS4	WS5	WS6	WS7	WS8	WS9	WS10
	empty weight	10	10	10	10	10	10	10	10	10	10
	fuel weight	10	10	10	10	10	10	10	10	10	10
	icac	4	3	4	4	4	5	4	4	4	3
	tofl	5	5	5	5	5	5	5	5	5	5
	ldgfl	4	3	4	4	4	5	4	4	4	3
	co2	4	3	4	4	4	5	4	4	4	3
	nox	4	3	4	4	4	5	4	4	4	3
	stability/balance	5	5	5	5	5	5	5	5	5	5
	reliability	5	5	5	5	5	5	5	5	5	5
	safety	6	6	7	6	6	6	5	6	6	7
	passenger	4	3	4	4	4	5	4	4	4	3
	fuel capacity	2	2	2	3	2	2	2	1	2	3
	cabin noise	2	2	2	3	2	2	2	1	2	3
	rdt&e	2	2	2	3	2	2	2	1	2	3
	production	1	1	1	1	1	1	1	1	1	1
Take0ff/Cutbac	High-Lift Noise	9	9	9	9	8	9	9	9	10	9
	Trailing Edge Noise	6	6	7	6	6	6	5	6	6	7
	Aft Fan Noise	10	10	10	10	10	10	10	10	10	10
	Forward Fan Noise	5	5	5	5	5	5	5	5	5	5
	Turbine Noise	7	7	8	7	7	7	7	7	7	8
	Nozzle/Jet Noise	9	9	9	9	8	9	9	9	10	8
Approach/Landing	High-Lift Noise	10	10	10	10	10	10	10	10	10	10
	Trailing Edge Noise	6	6	7	6	6	6	5	6	6	7
	Aft Fan Noise	10	10	10	10	10	10	10	10	10	10
	Forward Fan Noise	4	3	4	4	4	5	4	4	4	3
	Turbine Noise	7	7	8	7	7	7	7	7	7	8
	Nozzle/Jet Noise	5	5	5	5	5	5	5	5	5	5

Figure 6b. Weighting Scenarios.

The perturbation process ensured objectivity and robustness. Results were visualized as radar charts, as shown in Fig. 7, which showed the technology rankings for different weighting scenarios. Three radar charts were created per mapping scenario corresponding to three noise scale factors (0, 0.5 ,1). Radar charts with different mapping scenarios were compared with one another to investigate the variability of the ranking with small perturbations in values chosen in the Pugh Evaluation Matrix. Figure 7 shows the results obtained for inlet technologies, for NSF =0.5. Since the color-coded lines do not cross each other, the technology ranking results remain the same despite perturbations in the inputs. Therefore, the subjective rankings applied to the technologies of Fig. 7 may be considered to have provided an accurate assessment. For the most part, the results as a whole showed that technology rankings did not vary appreciably with weighting scenario. This indicated that the relative rankings were robust, and did not depend on small perturbations of the weights chosen for each design criterion.

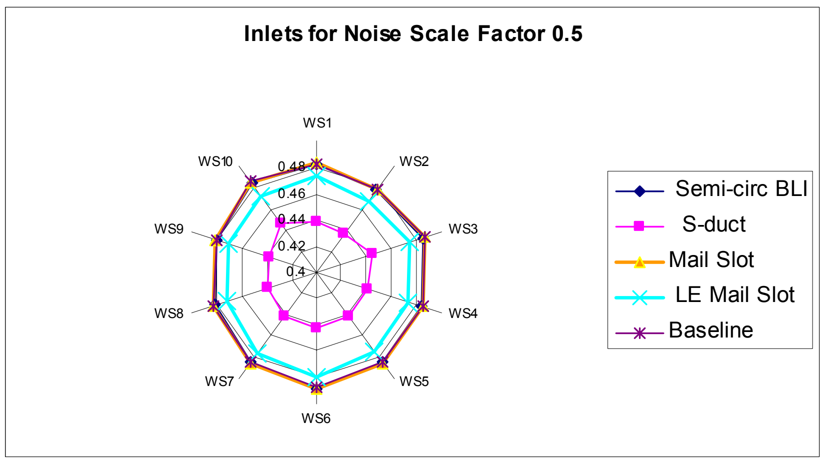

Figure 7. Radar Chart Shows Robustness in the Results.

V. Probabilistic Systems Analysis

Once the individual technology impacts were understood, the next step was to consider promising propulsion/airframe configurations integrated into the whole vehicle system. Possible vehicle configurations were formed by combining selected PAA technologies from the Morphological Matrix. However, neither time nor resources would allow all feasible configurations to be investigated further; therefore, those with the most promising technologies for the best noise reduction and least weight, performance, and cost penalties were selected based on the TOPSIS results and available analysis tools. A more detailed quantitative assessment was needed; therefore, a systems analysis was performed to evaluate the weight and performance for the candidate propulsion configurations using the following NASA codes: FLOPS, NPSS, WATE. FLight OPtimization System (FLOPS) is the aircraft performance and sizing code, developed at NASA Langley Research Center. Numerical Propulsion System Simulation (NPSS) is a flow path and cycle analysis code developed at NASA Glenn Research Center for propulsion system design and analysis. Weight Analysis of Turbine Engines (WATE) is a propulsion system weight prediction code, developed at NASA Glenn Research Center. These codes were used to simulate the effects of the technologies on a whole vehicle, and assess quantitatively the performance of the aircraft while flying a BWB-type aircraft flight mission.

The system modeled was a notional 300 passenger BWB-like transport powered by two General Electric (GE) GE-90-like engines. Technologies and design concepts were modeled by changing appropriate input parameters in the analysis codes. FLOPS was used to compute the BWB's cruise range given it's mission definition, size, and weight. NPSS and WATE were used to model the engine cycle and aeromechanical performance of the GE-90-like engine and produce engine state tables for use in FLOPS.

The baseline BWB's size and gross weight was held fixed and the mission range was chosen as the measure of merit for comparison of configurations. Uncertainty in the design variables, due to the revolutionary nature of the aircraft and propulsion configurations, made a deterministic point design difficult to obtain. A probabilistic assessment was therefore chosen as a more appropriate approach. This enabled bookkeeping of assumptions, a quantification of the uncertainty in the inputs, and propagation of that uncertainty into the performance results obtained. Ranges and distributions were assigned to the design variables, run through a Monte Carlo simulation, and probability density functions were obtained. Triangular distributions were assigned to the input variables, due to the availability of "minimum," "maximum" and "most likely" values, as shown in Fig. 8.

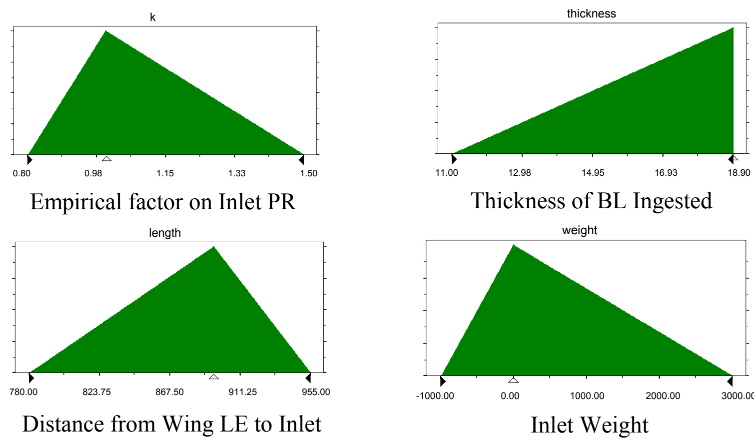

Figure 8. Triangular Probability Distributions.

The Monte Carlo simulation picked random values within the range and distribution assigned for each input variable. One thousand Monte Carlo cases were run through the analysis tools for performance and weight analysis.

JMP®, a statistical package, was used to regress the runs for visualization and analysis. JMP® provides a dynamic parametric visualization utility called the Prediction Profiler, as shown in Fig. 9. The Prediction Profiler enables the designer to view the responses as a function of the individual input design variables, and visualize through interactive manipulation how each design variable impacts each response. The red dotted lines are dynamic hairlines that can be moved left and right, and the black lines shows whether the design variable produces an increase or a decrease in the response. The steepness of the slope indicates the magnitude of the impact, and the actual values can be read in the red fonts. A desirability function is also available, as an external optimizer. The designer can choose to minimize, maximize, or optimize any response and JMP® will adjust the design variable values to obtain the desirability set.

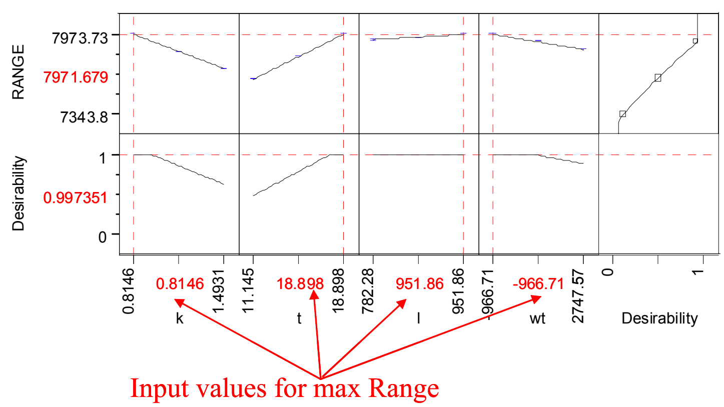

Figure 9. Parametric Sensitivity Study using a Prediction Profiler.

The probabilistic results from the Monte Carlo simulation are shown in the form of Probability Density Functions (PDFs) and Cumulative Distribution Functions (CDFs), Figs. 10 and 11. The PDF demonstrates how the uncertainty in the input variables contributes to the variability in the response. For the example shown in Fig. 10, the a/c with Semi-circular BLI inlets can have a range between 7,343 - 7,904 nmi. However, it seems that it is more likely to be around 7,666 nmi.

The CDF plots, which are the integrated PDFs, illustrate the confidence of obtaining a result greater than a particular target value. The higher the Range value, the less confidence there is in meeting or exceeding it. For the BLI example shown in Fig. 11, the plot shows that there is 76.2% confidence that the a/c range will be equal or larger than 7,500 nmi, which corresponds to the baseline BWB range. The 95% confidence line is generally looked at for "near certainty", which indicates a 7,428 nmi range. This value is not much lower than the baseline value, which means that it is very likely that BLI inlets will increase the BWB 300's Range capability.

As this study has shown, the use of probabilistic analysis enabled a quantification of the uncertainty in the results based on the uncertainty in the input. A more realistic design space was produced, and a measure of confidence of obtaining the project goals was given.

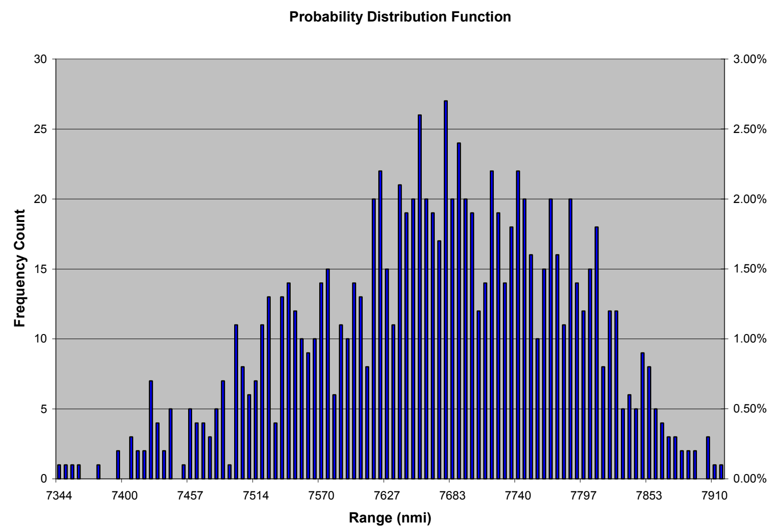

Figure 10. Probability Distribution Function.

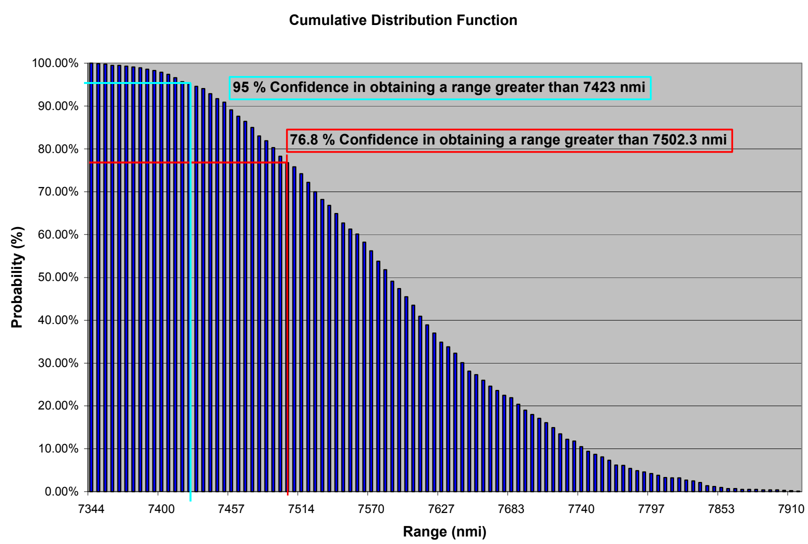

Figure 11. Cumulative Distribution Function.

VI. Conclusion

This paper has demonstrated the use of MADM techniques and probabilistic analysis in providing initial technology assessments for the Blended-Wing-Body transport. Pugh Evaluation Matrices and TOPSIS have been used in the past; however, the introduction of noise requirements, which are non-traditional figures of merit, into the conceptual design decision process makes this application of the method unique. In addition, the Noise Scale Factor allowed greater flexibility and control for the end user. For example, designers focused on environmental or community impact concerns who care mainly about the magnitude of obtainable noise reduction would choose a high NSF, with technologies that may have high weight/performance/cost-associated penalties and be willing to pay that price for a low noise design. However, designers focused more on economic viability would more likely choose a design based on technologies with an NSF that presents lower performance/noise tradeoffs.

In traditional conceptual design, performance (weight, range, fuel burn, etc.) has been the primary or only figure of merit. Additionally, the traditional commercial transport paradigm has been the familiar wing and tube with turbofan engines. It stands to reason, that the traditional conceptual design tools that have evolved over the last 40 years are focused on this paradigm and are not well suited to unconventional revolutionary aircraft configurations and technologies. Even though this paper focused on just one unconventional configuration, the BWB, and one non-traditional figure of merit, noise, the number of potential PAA technologies and the revolutionary nature of those technologies precluded the use of the traditional conceptual design tools. The methods required for analysis of these revolutionary concepts and technologies, when available, are typically computationally intensive and not well suited to conceptual design. This creates a dilemma for the researcher in that he must either have unlimited resources or limit the number of technologies to be analyzed in more detail. The MADM process influences the designer to fill in the gaps in understanding of the tradeoffs involved in a whole system and provides a rational path from conceptual design, to preliminary design, to detailed design. Probabilistic design allows the use of existing available design tools for revolutionary concept analysis by realizing and quantifying the uncertainty in the results associated with the unavailability of resources or higher order fidelity tools for a more detailed study.

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